Frontiers of seismology

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1 95% probability ellipses of locations of underground nuclear tests DPRK1–5 around Mt Mantap, North Korea, found using (left) body waves (Myers et al. 2018); (right) surface waves; overlain on topography. Green: DPRK1; blue: DPRK2; red: DPRK3; yellow: DPRK4; magenta: DPRK5. Surface-wave locations are at the mountain crests. (Google Earth)

Frontiers of seismology

Anton Ziolkowski and fellow organizers look back at the British Seismology Meeting 2019, which discussed events of all scales as well as new hardware and software techniques.

The British Seismology Meeting 2019 took place at the University of Edinburgh over three days, 4–6 September. The first British Seismology Meeting, BSM2017, was held in Reading in April 2017 (Lieser *et al.* 2018); there had been earlier seismology meetings in the UK, but no wide-ranging cross-disciplinary meetings since Frontiers of Seismology in Edinburgh 2009 (Sargeant *et al.* 2009). In his welcoming address at BSM2017, Dmitry Storchak expressed a wish that it would be the first in a series of such meetings, which he thought should become a regular event, perhaps every two years. At the end of the BSM2017 meeting, Anton Ziolkowski offered the University of Edinburgh as a potential venue for BSM2019.

BSM2019: Frontiers of Seismology attracted about 70 scientists from the UK and abroad, to present and discuss seismological research, establish new contacts and strengthen existing links. A feature of the meeting was that all posters were available in a large space adjacent to the lecture theatre for viewing, presentation and discussion for the whole period, including coffee breaks, lunch and evening drinks. Feedback from the meeting was very positive. This article presents a brief summary of each session.

Human-induced seismicity

Dmitry Storchak (International Seismological Centre, ISC) was in the chair and the session began with invited speaker **Stephen Myers** (Lawrence Livermore National Laboratory, USA), who presented an overview of a multidimensional seismological analysis performed by several specialist groups on the six underground nuclear tests announced by the Democratic People's Republic of Korea (DPRK). These tests occurred between 2006 and 2017 with magnitudes ranging between 4.1 and 6.1 and best-fitting yields from 1.7 kt (TNT equivalent) for DPRK1 to 149 kt for DPRK6, with corresponding depths of 421 and 636 m. The differences in published relative locations are considerably larger than the reported uncertainties. Figure 1 shows the differences in locations determined by body waves and surface waves. Analysis of small, unannounced events after the 2017 event in the vicinity of the test site showed that they were consistent with either a cavity collapse or natural seismicity in the area.

"Discrimination between natural and induced earthquakes remains a challenge"

Corinna Roy (University of Leeds) discussed the importance of robust uncertainties in local magnitude determinations of induced earthquakes for use in the so-called "traffic light systems" that are often employed to control production activities in oil and gas, geothermal, mining and other industries. She pointed out the importance of knowing the underlying uncertainties in the velocity models and source locations as well as station site effects in the determination of ultimate magnitude values currently used to make stop/restart decisions.

Stephen Hicks (Imperial College London) pointed out that the earthquakes induced by various subsurface activities have become a serious issue of concern internationally, yet discrimination between natural and induced earthquakes remains a challenge. He presented a detailed examination of the 2018–19 Surrey, UK, earthquake sequence – a shallow earthquake swarm close to hydraulic fracturing operations – and concluded that the earthquake swarm is unlikely to have been caused by the hydrocarbon activities. The evidence includes poor correlation of the timing of the start of seismic and industrial activities, earthquake source mechanisms consistent with the predominant general regional state of stresses, volumes of reinjected water too small to cause the required stresses, and extraction volumes too small to cause possible pore pressure transfer that could explain the earthquake swarm at some distance away from the industrial site.

Anton Ziolkowski (University of Edinburgh) discussed determination of source-time functions and yields of the last five DPRK nuclear tests from seismograms of just one near-field seismic station (MDJ in China). The procedure involved elimination of path effects using ratio filters and fitting Blake explosion source models to these filters, followed by calibration of source-time functions for yield using published data from the Nevada Test Site. The modelling showed that the elastic radii of the sources ranged from about 200 m for the 2009 event (USGS magnitude 4.7) to about 700 m for the 2017 event (USGS magnitude 6.3).

A poster by **Sheila Peacock** and colleagues (AWE Blacknest) noted that high-frequency (0.1–0.5 Hz) Rayleigh waves received at stations ~400km from the DPRK tests scale with the body-wave magnitude (m_b) (measured on P waves) at frequencies >~0.4Hz, possibly constraining the model of P and Rayleigh-wave production by underground nuclear tests.

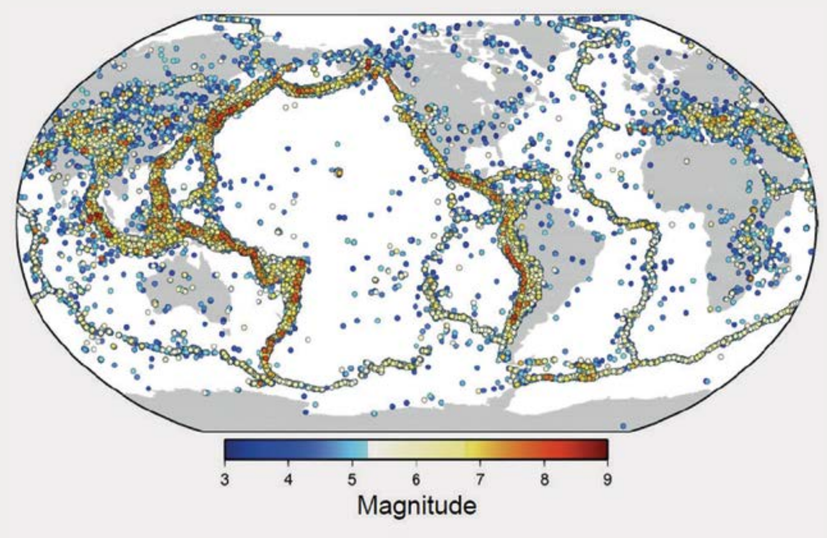
Deep mantle, volcano seismology, rock physics

Andrew Bell (University of Edinburgh) chaired this wide-ranging session, covering aspects of seismology from the smallest to the largest scales. Invited speaker Atalay Ayele (Addis Ababa University, Ethiopia) presented an overview of some of the seismic activity associated with rifting and magmatism in Ethiopia. The region of Afar and the northern Main Ethiopian Rift has been a site of more than 20 earthquake sequences in the last few decades, recorded by a small number of permanent seismic stations and larger temporary deployments. Seismicity includes both high-frequency volcano–tectonic sequences, hybrid earthquakes and more unusual low-frequency earthquakes. Most seismicity in these areas is associated with magma movement and emplacement, e.g. the 2005 Dabbahu volcanic episode, highlighting the need for funding for improved seismic monitoring to better understand volcanic processes and constrain the associated volcanic and seismic hazards.

Joseph Asplet (University of Bristol) talked about his studies of global-scale shear-wave splitting (birefringence) in the mantle. The azimuthal anisotropy of the lowest layer of the mantle (so-called D″ layer) was estimated from SKS and SKKS phases (i.e. S waves that convert to P waves on entering the Earth's liquid core, and back to S waves on leaving it), providing new constraints on mantle dynamics. He presented a new approach to identify shear-wave splitting discrepancies, finding 36 discrepant event-station pairs that map to a region of anomalous D″ anisotropy beneath the eastern Pacific, consistent with observations using other approaches. His interpretation is that the anisotropy results from the lattice-preferred orientation of post-perovskite, a mineral with highly anisotropic crystals that forms from olivine at the high pressures found at that depth. The cause of the widespread alignment of the anisotropic crystals might be flow of subducted material from the Farallon slab at the core–mantle boundary.

Alexis Cartwright-Taylor (University of Edinburgh) presented results from a new set of rock deformation experiments where microcrack growth was imaged in 4D using X-ray microtomography. These triaxial compression experiments were undertaken at the SOLEIL synchrotron in France, using samples of Ailsa Craig microgranite which is prized for its homogeneity. Samples in which cracks were induced by heating to 600°C were compared with unheated samples. Using data extracted from the X-ray images, cracking in the unheated samples was related to the accumulation of increasingly distributed damage and rapid onset of failure, whereas the heated samples, already pervaded by cracks, displayed a slower approach to failure consistent with a second-order phase transition.

Georgios Papageorgiou (University of Edinburgh) presented his work on developing models for the propagation of seismic waves in partially saturated fractured rocks. Understanding seismic anisotropy in these rocks is important for hydrocarbon exploration and production as well as for monitoring CO_2 storage. Frequency-dependent anisotropy in fractured rock is well described by an effective fluid mobility that depends on both the relative fluid permeabilities and the fluid distribution. His model explains experimental results in synthetic sandstones with coin-like fractures that are partially saturated with brine and CO_2. Experimental measurements of Vp and the two shear-wave velocities can be interpreted in terms of the combined effects of viscous flow in pores and "squirt" flow of fluids expelled from thin cracks into rounder pores.



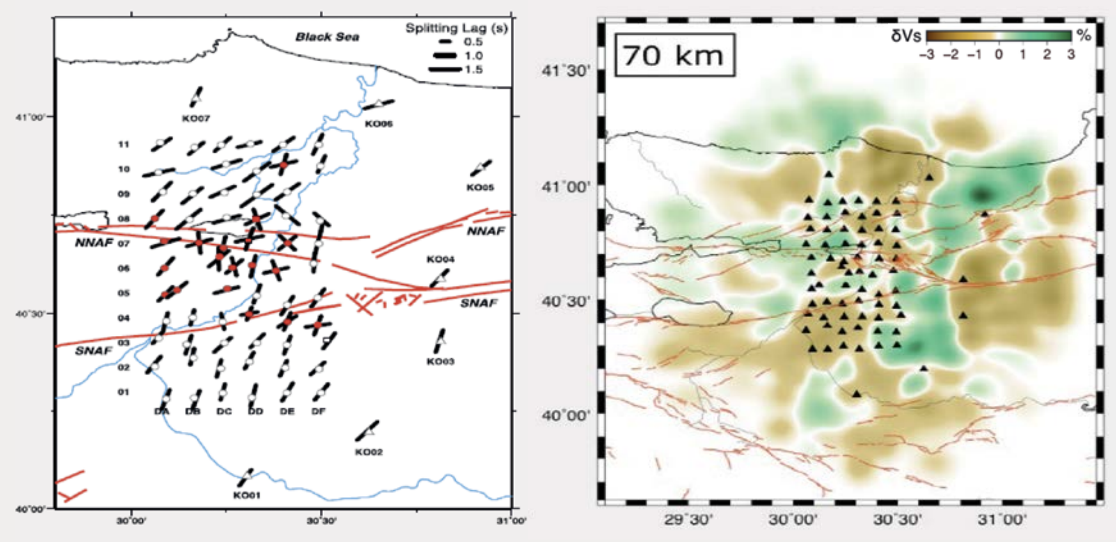
2 *Global magnitudes and seismicity from the ISC-EHB catalogue.*

Kai Deng (University College London) presented a strategy for analysing P-wave azimuthal anisotropy near the core–mantle boundary (CMB) using seismic data for M≥6 earthquakes from large-aperture seismic arrays. The analysis of PcS_{diff}, an evanescent diffracted leg of the core-reflected PcS wave (incident as a compressional P wave and reflected off the core as a shear S wave), indicates a negative P-wave velocity gradient in the bottom 200km of the mantle near the CMB. Jennifer Jenkins (University of Cambridge) presented analysis of small-amplitude seismic phases occurring just before and just after ScS (the shear wave reflected off the core as a shear wave) using seismic data from the US Transportable Array in Alaska and events in the Tonga–Fiji subduction zone. These phases are caused by layered CMB velocity structures. The analysis led to a detailed map of small-scale ultra-low-velocity zones (ULVZs) near the CMB under Hawaii. Andrew Bell (University of Edinburgh) and colleagues presented seismic data from the Galapagos Islands to show that dynamic stress perturbations from large earthquakes can promote seismic and volcanic activity at distances beyond those associated with static stress changes. The propensity for dynamic triggering of local volcano–tectonic seismicity at Sierra Negro volcano increased over five years as a shallow magma chamber inflated and raised stress levels prior to eruption. Following eruption onset and rapid deflation of several metres, the triggering response was no longer observed for the same dynamic stress perturbation, indicating a rapid recovery of repose stress levels.

Data and software

Alice Walker (ABConsulting, Edinburgh) as chair introduced Dmitry Storchak (ISC) who presented recent ISC data and service releases. ISC's mission is to produce the most long-term and complete summary of instrumentally recorded seismicity on a global scale and is making available source mechanisms for moderate to large earthquakes for the periods 1938–91 and 2011–16. Following a decrease in reporting of depth phases, ISC has begun to fill in the gaps with online waveforms for events with magnitude 4.8 and greater, worldwide. A new ISC service allows researchers or groups to archive catalogues/bulletins of seismic events, results of critical review, regional seismicity, Earth-structure studies, velocity models and notable earthquake observations. New funding is critical to maintaining the excellent service that ISC provides. Storchak asked researchers to consider including the ISC in grant applications and project proposals.

"ISC's mission is to produce the most complete summary of instrumentally recorded seismicity on a global scale"



3 (Left) *Direction of anisotropy.* **(Right)** *Magnitude of shear-wave splitting.*

Richard Luckett (British Geological Survey, BGS) reported on the UK Geoenergy Observatories (UKGEOS) project, which has established two new centres for world-leading research in Glasgow and Cheshire. Their aim is to monitor underground energy technologies and increase efficiency and sustainability of new and established energy and storage technology. The knowledge generated will contribute to the responsible development of new energy technologies. The planning application for the Cheshire observatory was approved in July 2019 and drilling should start in April 2020. Drilling is underway in Glasgow and seismic data are already available. The centres are intended to have a lifespan of at least 15 years. The data will be made available to researchers from industry and academia (both UK and international).

Burak Sakarya (ISC) explained how ISC had been refining its original EHB dataset of well-recorded seismic events (earthquakes and explosions), originally developed with procedures dating from 1998. A cleaner and more robust dataset was required for tomography and seismicity studies on regional and global scales. The ISC-EHB now includes 170550 events with prime magnitude >3.75. The algorithm for refining the dataset is run until a stable location is achieved, before progressing to the next step. The ISC-EHB is now one of the most refined global seismicity catalogues and is freely available from the ISC website (isc.ac.uk/isc-ehb). It will be extended beyond 2016 as soon as the annual ISC Bulletin reviews are completed. Figure 2 shows results from the ISC-EHB. At the end of his talk, Sakarya launched the 2019 earthquake prediction competition, which asked BSM2019 participants to predict in which region of the world the next magnitude >5.0 earthquake would occur in the following 24 hours; the winner was announced at the conference dinner.

Frederik Tilmann (Deutsches GeoForschungsZentrum, GFZ) presented a poster on behalf of Carlo Cauzzi (Observatories and Research Facilities for European Seismology, ORFEUS), who was unable to attend. ORFEUS is a non-profit foundation promoting seismology in the Euro-Mediterranean area through the collection, archive and distribution of digital seismic waveform data, metadata and derived products. Among its goals are: (a) development and coordination of waveform data products, (b) coordination of a European data distribution system and support for seismic networks in archiving and exchanging digital seismic waveform data, (c) encouragement of the adoption of best practices for seismic network operation, data quality control and data management; (d) promotion of open access to seismic waveform data, products and services for the broader Earth-science community. These are achieved through services targeting a broad community of seismological data users. Particular attention is paid to enhancing ORFEUS services to tackle the challenges posed by the big data era, with emphasis on data quality, improved user experience, and implementation of strategies for scalability, high-volume data access and archive. Among the many planned activities, they are looking at cloud-based processing to minimize data transfer, adapting the ORFEUS services to the objective load on the system, and improving the capacity of ORFEUS to integrate, process and distribute massive datasets that are too large to be incorporated in the present workflows. Kathrin Lieser (ISC) presented a poster on the ISC Rebuild project, which aims to improve the value of the ISC Bulletin by homogenizing methods across more than four decades of data to guarantee consistency of locations and error estimates through the entire period. Results from the first 21 data years (1964–84) are now publicly available as part of the ISC Bulletin and results for the next 20 years will be published soon.

"The ISC-EHB is one of the most refined global seismicity catalogues and is freely available"

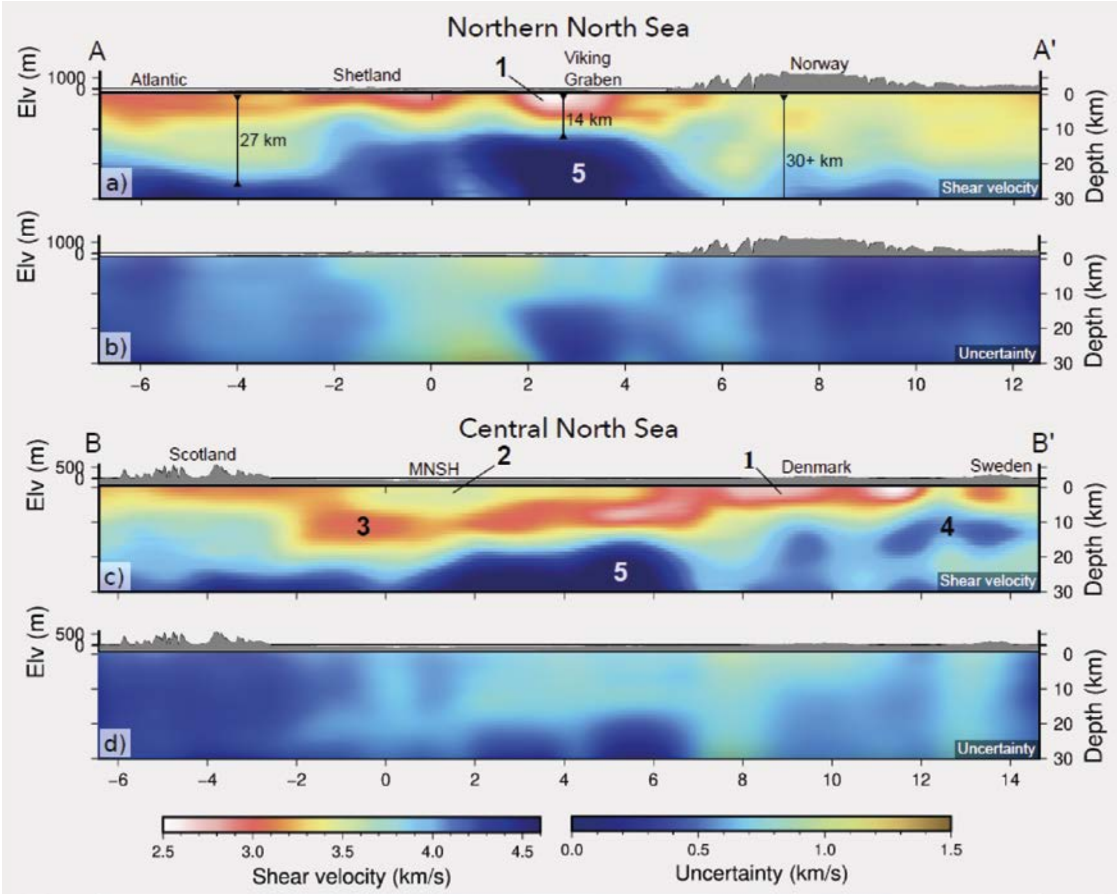
Lithosphere imaging

Calum Macdonald (University of Edinburgh) chaired the first lithosphere session, beginning with invited speaker Stephen Hicks (Imperial College London) who presented the latest understanding of the Lesser Antilles subduction zone, where the tectonic plate underlying most of the Atlantic Ocean bends to travel downwards into the mantle beneath the Lesser Antilles island arc in the Caribbean. By inverting the amplitude spectra of P and S waves from more than 350 earthquakes recorded by an array of 34 ocean-bottom seismometers, he identified variations in the attenuation of P and S waves. The mapped P- and S-wave attenuations were then used to infer the temperature, viscosity and volatile content of the subsurface. Behind (westwards of) the island arc, a zone of anomalously high shear attenuation has been identified in the mantle above the descending plate. This implies the presence of fluids rising from the subduction zone. The study has improved our understanding of the subduction process.

Emma Chambers (University of Southampton) showed how the joint inversion of Rayleigh waves from both distant earthquakes and ambient noise could be used to identify variations in crustal thickness of 16–40 km in the northern East African Rift. Variations in shear-wave velocity were also used to infer melt content in the different crustal blocks.

David Cornwell (University of Aberdeen) used a dense array of seismometers to study the structure of the North Anatolian Fault. Figure 3 shows that there are variations in the direction of anisotropy and the magnitude

4 *Cross-section slices through the new 3D shear-wave velocity model of the North Sea and surrounding landmasses at latitudes of 56.0° (A) and 60.0° (B), from Emily Crowder's talk. Standard deviation values for uncertainty in the velocity models are shown below each cross-section. Velocity anomalies: (1) Sedimentary basins with low velocities; (2) relatively higher velocities of Mid North Sea High (MNSH); (3) anomalously low velocities in mid-crust; (4) relatively high velocities around Trans-European Suture Zone; (5) significantly elevated velocities – mantle influence, thinned crust.*



of shear-wave splitting in the different zones between branches of the fault. These variations help to explain the development of this active fault zone.

Itahisa Gonzalez Alvarez (University of Leeds) introduced a method for investigating scattering of seismic waves by heterogeneities in the lithosphere (the rigid crust and uppermost mantle) using teleseismic waveforms, which will be applied to a dataset from Australia.

The University of Cambridge was strongly represented in the poster session. Deborah Wehner (Cambridge) presented a full-waveform tomographic inversion that will be used to determine the crustal structure in Borneo. Conor Bacon (Cambridge) received the student poster prize for his work on constraining seismic anisotropy in the Icelandic rift zone using shear-wave splitting measurements. Tim Greenfield (Cambridge) used a regional earthquake catalogue to characterize the subduction zone beneath Northern Sulawesi and better understand present-day deformation. Eoghan Totten (University of Oxford) presented his work on full-waveform body-wave tomography, which can be used to better image subduction zones.

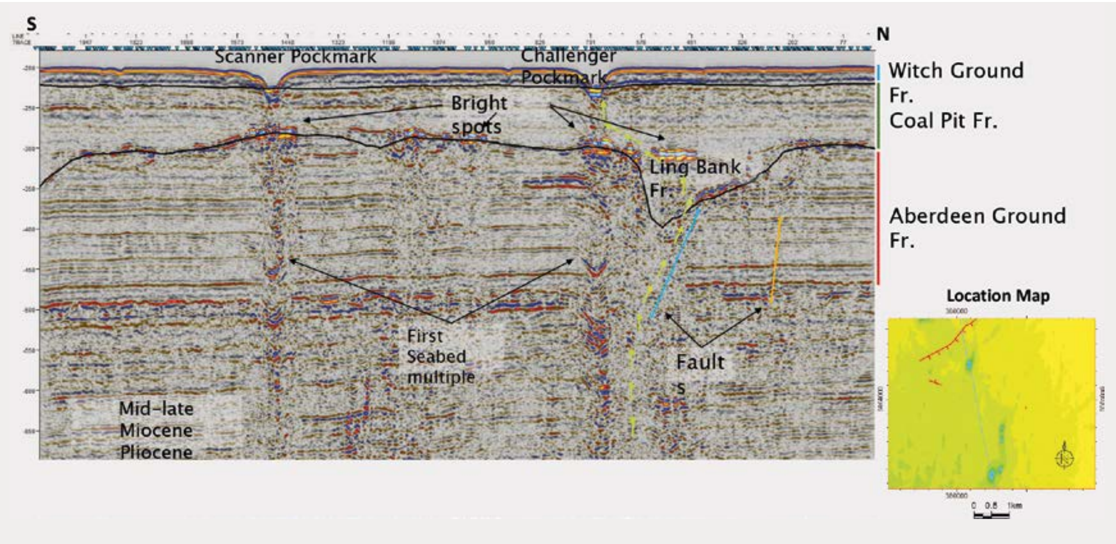
Andrew Curtis (University of Edinburgh) chaired the second lithosphere session, starting with invited speaker Amy Gilligan (University of Aberdeen) who discussed post-subduction processes beneath Borneo. The research team used late arrivals of mode-converted seismic waves following the direct P wave from distant earthquakes to map lower-crustal and upper-mantle interfaces beneath 70 seismometers, adding further information from surface-wave data. The crust varies in thickness between 25 and 45 km and the structures indicate that the crust underlying the Dangerous Grounds sea strait offshore Sabah may be underthrust beneath the ~2000 m high Crocker Range. The global 660 km discontinuity in mantle seismic velocity appears to be depressed, indicating that cold material from a previously subducted piece of tectonic plate may be present.

Omry Volk (University of Cambridge) discussed a study of the variable crustal structure in Iceland, including a noticeable mid-crustal discontinuity at about 20 km depth. Volk and collaborators analysed the velocity and radial anisotropy structure of the crust and upper mantle using phase-velocity dispersion measurements from surface waves. They showed that structures imaged by horizontally and vertically polarized S waves (SH and SV) differed significantly with depth. In the upper crust they find that velocity of SV>SH, which they attribute to vertically oriented cracks and dykes, while in the lower crust they find SV<SH, and the radial anisotropy displays weak azimuthal dependence with lower velocities parallel to the plate-spreading direction. This suggests that the lower crust comprises layered sills of anisotropic material which flows horizontally, in part parallel to the spreading direction.

Emily Crowder (University of Aberdeen) then presented a new tomographic shear-wave velocity model beneath the North Sea and surrounding land masses down to 40 km depth. This was constructed using five years of ambient noise data recorded on 54 seismometers in the UK, Scandinavia and the northern European mainland. The main source of ambient noise is the North Atlantic, where sea-surface disturbance by atmospheric pressure variations causes vibrations in the sea floor. Major North Sea sedimentary basins were imaged, in agreement with previously published sedimentary thickness maps. Thinned crust (~13–18 km) is observed beneath the Central Graben, whereas it is between 25 and 40 km thick elsewhere. Other structures were also found that had not previously been imaged. Results are shown in figure 4.

Near-surface seismology

Chair Christopher Browitt (University of Edinburgh) introduced invited speaker John Brittan (ION, UK) who began by asking, "What will follow on from our present capabilities in exploration seismic imaging?" One great hope is artificial intelligence (AI), but he also asked, "Can we really bypass difficult physics with AI?" He discussed the potential to move from the traditional open loop



5 *Interpretation of line 128, North Sea. The vertical axis is labelled at 50 ms intervals.* (From CHIMNEY data)

approach of progressing from raw data to final velocity model imaging of the subsurface in a straight line, to full-waveform inversion and a closed loop solution that iterates back to the field data. For the AI neural-net approach, another nonlinear solver, the answer is that AI may be better, but it still depends on the assumptions built in during the training of the AI.

Claiming that nonlinearity is your friend, because the family of plausible models is smaller, Andrew Curtis addressed the problem of achieving near-real-time 3D velocity models with uncertainty estimates using nonlinear ambient-noise tomography. Potential applications include monitoring induced seismicity, and earthquake and volcanic activity warnings. He used a surface wave, from noise, propagating across a dense array of seabed sensors to illustrate the methodology. Its speed is controlled by the velocity structure of sub-seabed sediments with uncertainty estimated during processing. Using trained neural networks achieves processing times, from data collection to model, of less than one hour.

As part of the NERC-funded CHIMNEY carbon capture and storage project, Calum Macdonald (Edinburgh) presented results from a detailed survey of a pockmark complex on the floor of the North Sea in order to characterize potential leakage pathways above CO_2 storage reservoirs. Some pockmarks, which are the result of past gas erosion through faults leading upwards, are hundreds of metres across. The principal data came from a dense array of multicomponent ocean-bottom seismometers receiving signals from an airgun source at long offsets, permitting fault structures to be identified through azimuthal anisotropy analysis. A full interpretation of these data, together with other approaches, remains to be completed, but patterns of polarized shear waves are clearly present, gas can be seen below the pockmarks, and results from a control area with no pockmarks show different characteristics. So, valuable results and understanding are emerging to guide carbon capture approaches for tackling climate change.

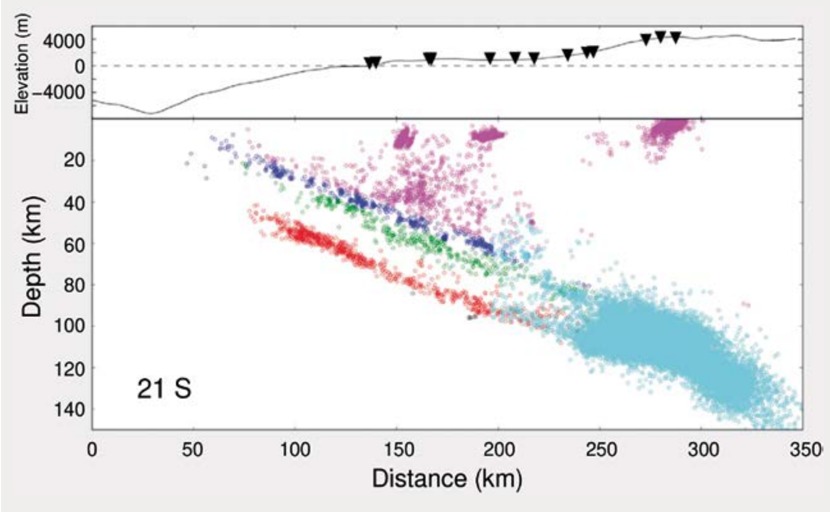
Mark Chapman (University of Edinburgh) picked up from Macdonald's presentation on the North Sea pockmark survey. He outlined the development of methods for using azimuthal anisotropy to identify chimney structures that might contain fractures enabling CO_2 leakage pathways to develop over carbon capture reservoirs. These methods are not without difficulties. So far, research has led to an indication that the anisotropy symmetry axis changes with depth, introducing another complication to the modelling problem. Figure 5 shows an interpreted line from the CHIMNEY data.

There were five posters in this session. Antony Butcher (University of Bristol) and colleagues analysed the main characteristics of a piezoelectric seismic system in a laboratory. The system was then compared with a conventional sparker-geophone system in a cross-hole field experiment at Hinkley Point C. Although most of the higher-frequency content was lost in the highly attenuating geology, the broad frequency range of the piezoelectric system with its very repeatable source allowed seismic attenuation between the boreholes to be measured, which was not possible with the conventional system. The resulting estimates of attenuation quality factor Q were $3<Q<20$, demonstrating the highly attenuating nature of the geology between the boreholes. Adam Klinger (University of Bristol) and colleagues presented the results of analysis of microseismic data collected during hydraulic fracturing operations in the Horn River Basin, British Columbia. The seismicity occurred at depth in the reservoir and in the underlying unit, indicating reactivation of pre-existing faults below the reservoir. Following analysis of 84 seismic spectra, they plan further investigations using forward modelling and statistical analysis. Louise Parkes (University of Edinburgh) and colleagues, as part of the CHIMNEY project, looked at evidence for anisotropy in a gas chimney using ocean-bottom seismometers. Noise-source analysis (beam steering) showed that there was good full-azimuth coverage of noise sources, and showed the dominant velocities to be between 300 and 800 m s^{-1}. They also showed potential for using the SPAC (spatial autocorrelation) method for quantification of anisotropy. Xin Zhang (University of Edinburgh) and colleagues used, for the first time, a 3D fully nonlinear tomography method applied to real data recorded on 3458 four-component sensors over the Grane field in the North Sea. They were able to determine an accurate shear-wave velocity model of the seabed and found that 1D inversion has significant errors, while 2D and 3D inversions improve results by including lateral spatial correlations in the inversion. Gina-Maria Geffers (University of Edinburgh) and colleagues looked at biases in estimating hazard from small earthquake catalogues using synthetic data. They found that, for small catalogues, the applied information criterion incorrectly selects the Gutenberg–Richter (GR) model as the best fit, giving a biased b-value. They use this finding to critique the magnitude bandwidth required to accurately distinguish a truly high b-value as opposed to a GR model being erroneously applied to rolling-off magnitudes.

"They presented the analysis of microseismic data collected during hydraulic fracturing"

Earthquake hazard, earthquake location

Ian Main (University of Edinburgh) acted as chair for this session. In her invited talk, Margarita Segou



6 *Cross-section through the Chilean subduction zone taken at 21°S with relocated seismicity superimposed. Magenta = upper plate events; blue = plate interface events; green = upper plane events; red = lower plane events; cyan = intermediate-depth cluster. Black triangles show seismometer positions on the ground surface.* (Modified from Sippl *et al.* 2018)

(British Geological Survey) described recent efforts to improve earthquake forecasting models using physical constraints such as fault geometry, finite rupture slip models and Coulomb stress modelling. The results show improved predictive power, comparable to or exceeding those from purely statistical triggering models, though significant challenges to implementing such forecasts in real time remain.

Gemma Cremen (University of Bristol) and colleagues compared recordings of ground motion from natural earthquakes with seismicity induced by shale gas and coal-mining activities in the UK. They determined an optimal attenuation model and showed that the shale-gas-related intensities (Preston New Road, Lancashire) were consistently higher than those of natural earthquakes at Newdigate, Surrey, while similar to or lower than those of the New Ollerton, Nottinghamshire sequence induced by coal mining. Timothy Craig (University of Leeds) presented a new, more automated approach to the problem of determining earthquake depth from seismic waves reflected from the surface directly above the focus ("depth phases") in a robust and reliable way. The method identifies seismic phases using coherency analysis and determines depth by optimal stacking significant volumes of data. The approach significantly improves results for small-magnitude earthquakes. Ross Heyburn (AWE Blacknest) in a poster showed how surface-wave data could be used to predict which seismic stations across the globe would receive the clearest depth phases. Tom Garth (University of Oxford and ISC) addressed a similar theme, by jointly inverting for earthquake source-time function, moment tensor and depth, and demonstrated that an improved depth resolution can be obtained, along with rigorous uncertainty estimates for these parameters, using an ensemble modelling approach.

There were three in this session. Hugo Bloem (University of Edinburgh) compared nonlinear to linear methods of determining an optimal design for receiver locations in a source localization problem using arrival-time data. The nonlinear methods performed better and, of these, the D_N method (Coles & Curtis 2011) outperforms the entropy metric in discriminating the locations of closely spaced earthquake sources. Peter Franek (ISC) addressed the issue of a consistent decline in the number of depth-phase picks reported to the ISC, a gap increasingly filled by the ISC determining its own, by analysing open access, whole-waveform data. The method also includes a determination of phase polarity, and has added more than 700 focal mechanism solutions for each data year in its reviewed bulletin. Stuart Nippress (AWE Blacknest) examined the problem of relocating seismicity on the relatively aseismic central Iranian plateau by combining seismic and geodetic data (from InSAR). They relocate over 400 events in the vicinity of the plateau, and used this to investigate the mode, magnitude and distribution of earthquake deformation across central Iran.

Earthquake seismology

Nicholas Rawlinson (University of Cambridge) was chair of the first earthquake seismology session, which started with invited speaker Frederik Tilmann (GFZ) reviewing a decade of seismic observation work in the neighbourhood of the north Chilean subduction zone. In this highly seismogenic region, caused by subduction of the Pacific plate below South America, GFZ has been responsible for developing an integrated plate-boundary observatory, which includes passive seismic (broadband and strong motion), continuous GPS, ocean-bottom seismometers, strain meters, interferometric synthetic aperture radar (InSAR), magnetotelluric and volcanic-gas sensors. These vast datasets have permitted very detailed analysis of earthquake rupture mechanisms and the distribution of seismicity and surface deformation. The use of relative location techniques coupled with a dense array of seismometers have allowed ~100 000 earthquake hypocentres to be determined with high precision. The resultant distribution of events reveals a clear triple subduction zone (see figure 6) associated with the downgoing slab. Machine learning was also applied to determine precise magnitudes of events in this very large catalogue. Coda-wave interferometry is a relatively new tool in seismology, with one application to continuously recorded data to allow small velocity changes over time to be detected. This method was applied to the dataset and provides insight into strain accumulation and release along active fault zones.

Jonathan Singh (University of Edinburgh) talked about seismic coda-wave interferometry. In particular, he explained the use of this method to estimate temporal changes in seismic-wave velocity, changes in source location and joint estimation of changes in both velocity and source location. He presented an application of the method to determine velocity perturbations in a sandstone that was heated and then allowed to cool. First arrivals of waves propagated through the rock were found to be unreliable to detect velocity changes, whereas coda-wave interferometry produced very accurate estimates. Application of a similar approach to detect changes in source location was found to be very accurate, provided the displacement divided by the dominant wavelength did not exceed ~0.5, although follow-up work has demonstrated that this threshold can be extended. This study has recently been published (Singh *et al.* 2019).

Abdelhakim Ayadi (Centre of Research for Astronomy, Astrophysics and Geophysics, Algeria; CRAAG) focused on the Algerian seismic catalogue, which is derived from both archaeological (historic) and macroseismic observations. Algeria lies at the boundary between the African and Eurasian plates, and is one of the most seismically active regions in the Mediterranean. Ayadi reported on the results of two recent initiatives, which are to analyse unpublished historical documents, and study Roman ruins from between 146 and 429 BC which show evidence of damage from strong earthquakes. The first initiative has so far recovered 286 events, and the associated database has been published in Harbi *et al.* (2015) and is available online. The second initiative has involved identifying the type of damage that could be sustained by stone structures and attempting to find evidence at archaeological sites. A variety of sites has been investigated including Thevest and Hippone, with earthquake evidence including fractures, tilt, rotation, column collapse and the extrusion of stone blocks from walls.

The two sessions on earthquake seismology included two associated posters that were displayed throughout the meeting. Ousadou & Ayadi (Centre de Recherche en Astronomie Astrophysique et Géophysique, CRAAG) presented new results from earthquake source analysis in the Cheliff Basin in Algeria. They analysed stress tensor variations using focal mechanism inversion, and compared the results with surface observations. Based on these results, they were able to build a stress field model for the whole Cheliff Basin. Kirsty Bayliss (University of Edinburgh) used log-Gaussian Cox process models, originally developed in ecology, to describe the spatially varying intensity of earthquake locations. These models are important for earthquake forecasting, which require a good understanding of the spatial and temporal patterns of seismicity. Yelles-Chaouche *et al.* (CRAAG) presented a poster on the estimation of source parameters for the largest earthquakes that occurred in Algeria over the last decade. A joint inversion of all focal mechanisms determined in this study and other previous studies was made to determine the regional stress field. They found that eastern Algeria is characterized by a strike-slip regime, whereas central and northwest Algeria is characterized by a compressive regime.

The second earthquake seismology session, with Sheila Peacock in the chair, started with Tae-Kyung Hong (Yonsei University, Seoul), who gave two fascinating South Korea-focused talks. The 2011 Tohoku, Japan, Mw9.0 earthquake was only 1300 km from South Korea and the coseismic strain accompanying it left the country ~2 cm wider than before, and more seismically active at the M ~ 5 level. Seismic-wave velocities in the Korean crust were reduced by 3% and have recovered gradually since then. By carrying out interferometry of ambient noise or local earthquakes using pairs of stations aligned along the great-circle path towards the earthquake, he showed that velocities and Vp/Vs ratios changed with time in a fashion that varied with azimuth away from the Tohoku direction, with biggest changes parallel and perpendicular to that direction. A similar analysis on the dense network of seismic stations in Japan (1349 stations) found similar variations confined to the topmost crust.

His second talk involved the M5.5 Pohang earthquake of 15 November 2017, which was shallow and caused considerable damage and some injuries. A question of liability has arisen for the operator of a geothermal project <1 km from the epicentre. The geothermal wells were not yet producing, and only small volumes of water had been pumped into them at the time of the earthquake. The local network of seismic stations, intended to detect much smaller events, was overloaded by the large-amplitude shaking, so only the first onset time could be used, reducing the accuracy of the depth determination. Uncertainty in the velocity models allows a wide range of depths between ~4 and 6 km. The base of the well is at 4 km, but a depth of 6 km would allow an explanation involving a hidden regional-scale fault within the zone stressed by the 2016 Gyeongju M5 earthquake. In addition, a M3.3 event a few months before and ~1.1 km below the eventual Pohang earthquake might have loaded the fault above and made it prone to failure.

"The announcement that the University of Cambridge will host BSM2021 was greeted with tumultuous applause"

Following on from Stephen Hicks's project tracing the water subducted beneath the Lesser Antilles, Felix Halpaap (University of Bergen) and Nicholas Rawlinson both addressed the anomalous small clouds of earthquakes in the mantle wedge in spots above the Hellenic (Mediterranean) and Izu–Bonin–Mariana (west Pacific) subduction zones respectively. These subduction zones are cold because old, cooled lithosphere is subducted as a cold slab into the mantle and cools it. Wet rocks of any age subducted into the mantle are dehydrated by various water-releasing mineral transformations, which occur at fixed temperatures. At zones subducting colder slabs these transformations occur at greater depths. The released water rises up the downgoing slab, then breaks through into the wedge of mantle above. A vertical trail of earthquakes shows it rising to the surface: these earthquakes show source mechanisms consistent with expanding fluid in addition to the usual tectonic fault slippage. The trail is narrow (a tube not a slit), so the "vent" in the slab/mantle interface must also be small. Its cause is a matter for speculation (fault, subducted seamount?).

The final talk was given by Marie Balon of Güralp, the seismometer manufacturer and one of the conference's sponsors. She described some welcome features of a new free-standing ocean-bottom seismometer. It can work at any orientation, can tell you its orientation (by means of MEMS and magnetometer "compass") and can transmit data on a high-frequency acoustic carrier signal to a floating receiver (buoy or ship) for immediate or via-satellite access. A bank of Li-ion batteries can give a month's continuous recording for an hour on charge. Close-in records of the subduction zone earthquakes described by the previous two speakers is in most places impossible without such ocean-bottom seismometers.

Closing remarks

The conference dinner was held in the evening of 5 September 2019 in the magnificent 1832 Playfair Hall in Surgeon's Hall. In a very entertaining after-dinner talk, Roger Musson (formerly BGS) proved that "seismology was invented in Edinburgh". Two prizes were awarded: Conor Bacon won £100 for best poster; the winner of the ISC competition to predict the next earthquake greater than magnitude 5.0 was won by Atalay Ayele, who received the £40 prize by guessing the M5.3 earthquake would occur in the Kuril Islands. The announcement by Nicholas Rawlinson that the University of Cambridge would host BSM2021 was greeted with tumultuous applause. ●

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